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RESEARCH ARTICLE

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Study on emissions reduction of DMCC engine with oxidation catalyst

Abstract A new combustion model diesel/methanol compound combustion (DMCC) is presented, in which methanol is injected into manifold and ignited by certain amount of diesel fuel. The results showed that DMCC remarkably decreased the emission of NO_x and the smoke, but increased the emission of HC, CO and PM. However, HC, CO and NO_x were dramatically decreased with a catalytic converter, and PM was also decreased compared with that of diesel engine. The testing results illustrated that, combined with oxidation catalyst converter, DMCC could improve engine emissions.

Keywords diesel, methanol, compound combustion, emissions, oxidation catalyst

1 Introduction

The diesel engine has always been highly valued because of its highest thermal efficiency. Compared with traditional internal-combustion engine, although great progress has been made in the improvement of modern internal-combustion engine, stricter emissions laws have been made by various countries in recent years, and increasingly rigorous energy problems brought about a new challenge to the further improvement of internal-combustion engine again. Great effort has been made to look for new, clean and high-efficiency combustion technique; and alternative fuel is found to be a practicable way to solve the problem of oil shortage and pollution caused by internal-combustion engine. Methanol is a kind of high oxygen content and low emission green alternative fuel that burns sufficiently and can be manufactured from coal. And China is a country with abundant coal reserves, whose technique of making methanol from coal is practicable, and the production cost is low too. Therefore, methanol is one of the ideal and practical alternative fuels in China. The efficient use of methanol is always in exploration because of its characteristics. A new combustion model which suited the technical level and energy condition of China was presented in Tianjin University in 2004. Igniting methanol by diesel, the PM and NO_x emissions of diesel engine are reduced simultaneously by using diesel/methanol compound combustion (DMCC) [1].

In recent research, it is discovered that compared with ordinary DI engine, DMCC engine decreases PM, NO_x and CO_2 emissions, but it increases HC and CO emissions [2]. Therefore, to burn methanol efficiently, it is obligatory to solve the problem of high HC and CO emissions in DMCC engine. According to DMCC control strategy [3], methanol is injected at the high or normal engine load, when the exhaust temperature rises up to catalytic converter light-off temp. Therefore, the experiment in this paper aims to reduce HC and CO emissions by installing an oxidation catalysis converter.

2 Experimental system and methods

Diesel/methanol compound combustion engine is transformed from a vertical, direct injection, water-cooled, four-stroke 490QDI diesel engine. The specifications of the test diesel engine are shown in Table 1.

Figure 1 outlines the experimental system. The main test facility in the experiment includes a CW160 eddy current dynamometer and an engine parameters control panel; two FCM-05 automatic transient-fuel-consumption meters to measure the consumption of diesel and methanol separately; a Ricardo flow-meter to measure the inlet air flow; an FQD-102A bosch digital opacimeter to measure the opacity of exhaust gas; PM is collected on the filter paper by partial flow dilution system exhaust test facility and weighed by a balance of gamma magnitude; HORIBA MEXA-7100 gas analyzer to measure the harmful emissions, such as NO_x, HC and CO. NO_x, CO and HC are measured by a chemiluminescent detector, a nondispersive infrared analyzer and a flame ionization detector respectively.

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Table 1 Specifications of test engine

Engine type	Bore/mm / Stroke/mm	Swept volume/L	Compression ratio	Declard power/kW / Speed/(r·min^{-1})	Maximum torque/Nm / Speed/(r·min^{-1})	Minimum consumption/(r·min^{-1})
Four-cylider/four-stroke	90/100	2.54	18 : 1	45.6/3 200	156.8/2 240	228

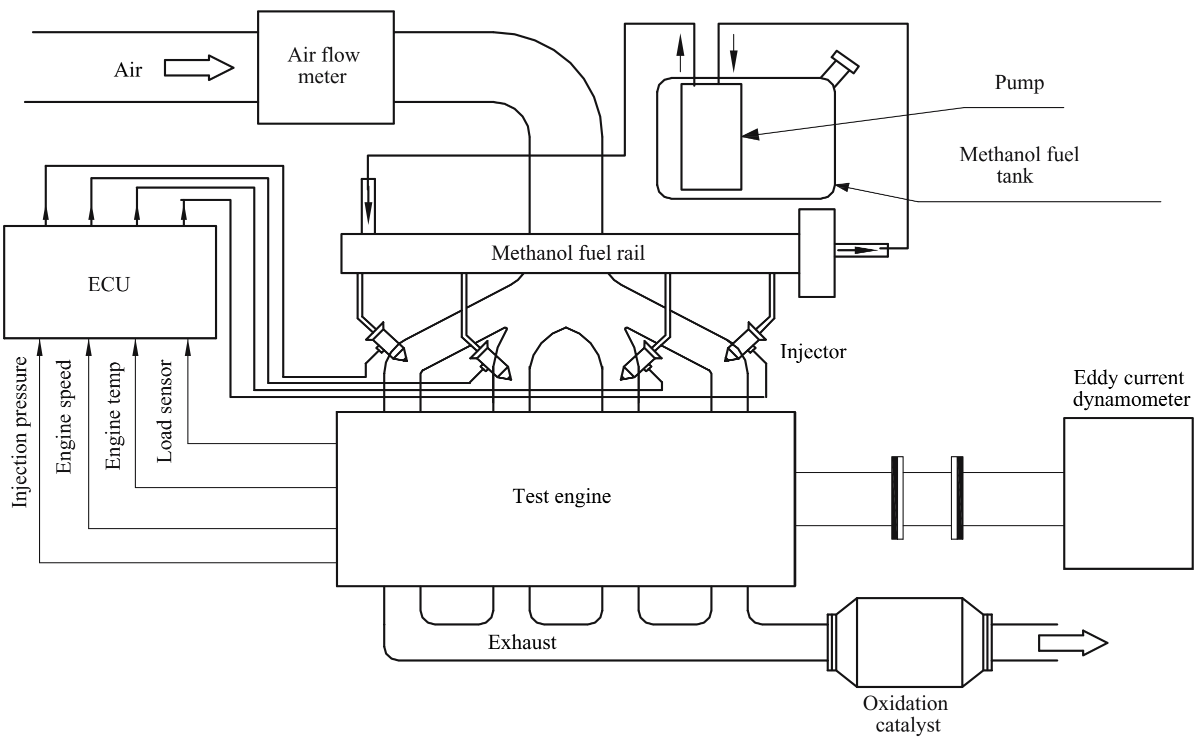

Fig. 1 Schematic of DMCC engine system

The experiment is conducted on three kinds of combustion modes, which are diesel engine, diesel/methanol compound combustion (DMCC) and DMCC with an oxidation catalytic converter respectively. The operating condition is the engine speed at 1 600, 2 200 and 3 200 r/min, which is the constant speed characteristic condition. The variation of emissions of three kinds of combustion mode is compared and analyzed. In the experiment, the proportions of methanol to diesel at the five operation conditions are 26.27%, 37.54%, 47.99%, 48.16% and 54.23%, respectively. The overall trend is that the replacement rate increases continually with the increase in load. According to the GB 17691-2001, 13-Mode on bench is adopted to measure the components of emissions. In the test, only 0# standard diesel is used to complete the entire mission, and original working condition (including speed, torque, temperature, etc.) is then restored by using DMCC mode to ensure the comparability of the results.

3 Results and analysis

3.1 NO_x emission comparison

Figures 2 and 3 show the comparison of NO_x emissions at the speed of 1 600 and 2 200 r/min using diesel only, using DMCC, and using DMCC with an oxidation catalytic converter respectively. In Figs. 2 and 3 and the following figures, “D” represents diesel engine, “D + M” represents DMCC mode, and “D + M with OCC” represents DMCC with an oxidation catalytic converter. It can be seen that NO_x emissions in DMCC and DMCC with an oxidation catalytic converter mode are lower than those in diesel mode at any speed. And the higher the speed is, the lower the NO_x emissions are. However, at a higher engine load the decrease amplitude is relatively small. In the three kinds of combustion modes, NO_x emission trends are alike, which increased with the increase in load; NO_x emissions of DMCC with an oxidation catalytic converter mode are higher than those of DMCC mode, but it is much lower than those of diesel mode.

According to kinetics of chemical reactions, three main conditions in which NO_x generates are high temperature, oxygen enrichment and high temperature duration [3]. Methanol is injected in intake branch. Because of its great latent heat of vaporization, intake temperature and the maximum combustion temperature are decreased. Meanwhile, the addition of methanol helps to reduce the duration of high-temperature combustion and increase combustion velocity. Therefore, it decreases NO_x emissions. However, because methanol is oxygen-bearing fuel which leads to an increase in

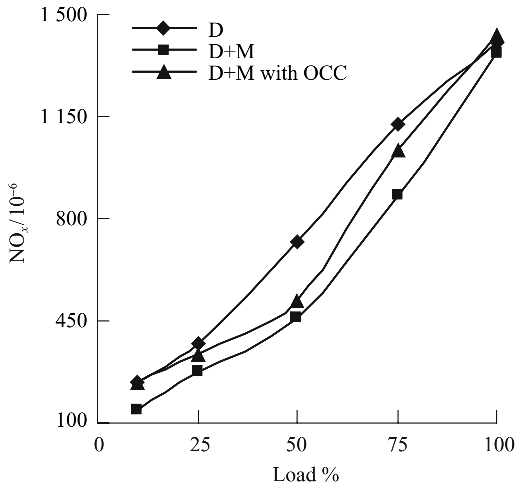

Fig. 2 NO_x emission at 1 600 r/min

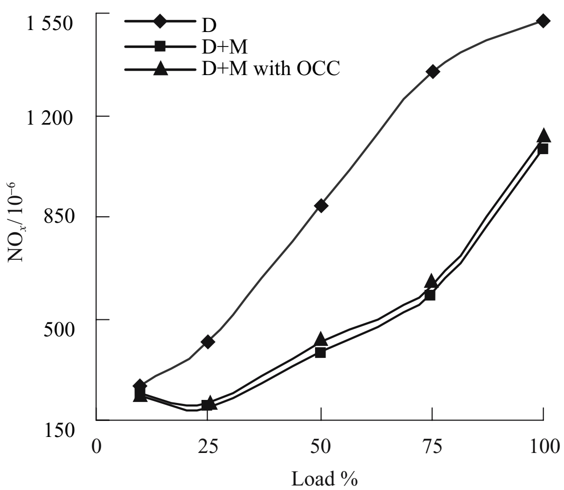

Fig. 3 NO_x emission at 2 200 r/min

excessive air coefficient of all the conditions, it will be conducive to the generation of NO_x. The role of these two factors in NO_x generation is reverse, so NO_x emissions in specific condition depend on the integrative effect of two factors.

Experimental results show that NO_x emissions in DMCC mode are lower than that in diesel engine mode at any speed. And the higher the speed is, the lower the NO_x emissions are. The main reasons for this is that, on the one hand, injecting methanol in intake branch leads to temperature decrease and reduces the duration of high-temperature combustion and increases combustion velocity. Thus it affects the generation of NO_x. On the other hand, the important effect of DMCC is to reduce combustion temperature, and decrease quantity of NO_x at high speed and high load. Because the generation of NO_x is relatively small at low speed, the injection volume of methanol is little and the difference of concentration of NO_x emissions between different modes is not much. But the high-speed and high-load condition is the phase that the generation of NO_x emissions grows sharply. At that time, a great deal of injection of methanol can reduce the intake temperature. And due to shortened combustion duration, the integrative effect causes obvious decrease in NO_x emissions in DMCC mode. In the condition of full load, due to the restriction of knock limit, the injection of methanol is decreased relatively, and the intake temperature begins to decrease consequently, which results in the decrease in different NO_x emissions between different combustion modes. The results show that DMCC mode has a remarkable effect on the reduction of NO_x emissions at high speed and high load. With an oxidation catalytic converter, NO_x emissions are increased appreciably. Oxidation catalytic converter is formerly a burner, so the exhaust air disposed by it burns again, which causes a small increase in NO_x emissions.

3.2 Soot emission comparison

Figures 4 and 5 show the comparison of soot at different combustion models. It can be seen that the soot of DMCC engine has remarkably been decreased, compared with that in diesel fuel only. The trend of soot change is nearly the same at different constant speed characteristics. A decrease of 50% of soot can be reached, which shows that methanol is effective in decreasing the soot through oxidation catalyst. At medium and low load, the soot almost disappears. Even at full load, the soot is below 1.0 RBU.

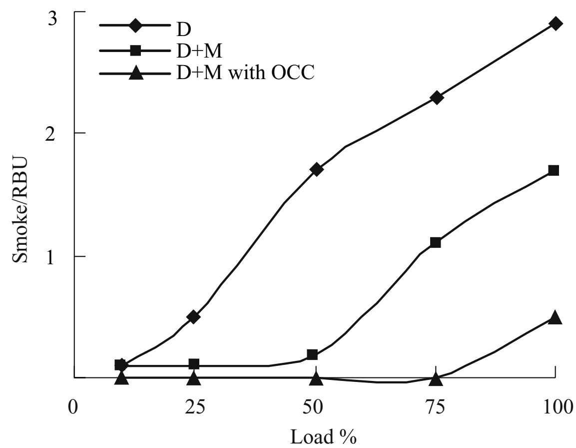

Fig. 4 Smoke emission at 2 200 r/min

The diesel engine injects diesel fuel at the end of compression stroke, and the fuel mixture is usually not uniform in the areas mixing with air, then soot will be produced because of dense combustible mixture. As the production of soot is related to the form of combustible mixture and the oxygen concentration in burning region, the mixture formed in DMCC mode which contains much oxygen itself, will help to decrease soot [4]. Compared with that of diesel fuel, the heat vaporization of methanol is higher, the number of cetane is less, and the flame propagation velocity is higher. When the engine runs at DMCC model, methanol is injected into the intake manifold and mixed with the air there during the intake process. When diesel is injected into the combustion chamber,

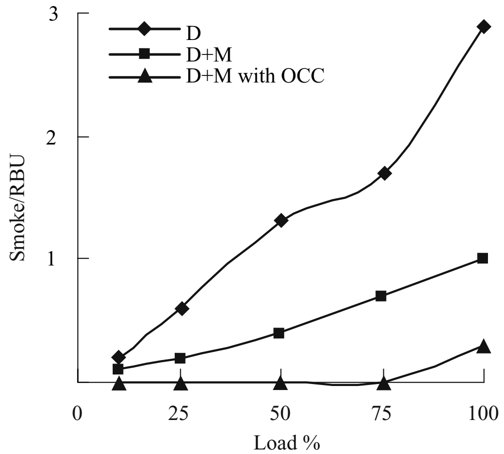

Fig. 5 Smoke emission at 3 200 r/min

methanol has become homogeneous mixture. Therefore, the combustion model prefers to pre-mixing combustion which increases combustion velocity and shortens combustion duration. Thus DMCC model decreases the production of soot.

The mechanism of the soot affected by methanol fuel can be analyzed as follows. First, soot will not be produced when methanol is burning. When methanol replaces some diesel fuel which produces soot, soot emission decreases naturally. Second and more importantly, methanol can create much free radical OH which is easier to act with the intermediates of the diesel molecule than other free radicals such as H and O. The equations which are most likely to form C_2H_2, H, O and OH are listed as follows

$$C_2H_2 + H \rightarrow C_2H + H_2 \tag{1}$$

$$C_2H_2 + O \rightarrow CH_2 + CO \tag{2}$$

$$C_2H_2 + O \rightarrow HCCO + H \tag{3}$$

$$C_2H_2 + OH \rightarrow C_2H + H_2O \tag{4}$$

$$C_2H_2 + OH \rightarrow CH_2CO + H \tag{5}$$

The activation energy of the reactions (1)–(5) are 22,243, 3,178, 12,110, 12,035 and 1,209 kJ/mol respectively. According to the priority principle of activation energy, the ability of OH to destroy acetylene is three times stronger than that of O and 20 times stronger than that of H. As the reasons just mentioned above, DMCC model can decrease soot on a large scale [5].

Soot is depressed deeply after getting through oxidation catalyst, because when the exhaust goes through oxidation catalyst, which burns some soot, the smoke intensity gets lower. The higher the speed, the load and the exhaust temperature are, the more active the catalyst is, and the lower the amount of soot is.

3.3 HC and CO emission comparison

Figures 6 and 7 show the comparison of HC and CO emissions at DMCC model with and without oxidation catalyst. It is obvious that HC and CO emissions of DMCC model are higher than those of diesel model. When the catalyst is installed, HC and CO emissions decrease rapidly. In high and medium load, HC and CO emissions are especially low, which are even lower than those of diesel model. This shows that oxidation catalyst has an obviously effect on cleaning the exhaust.

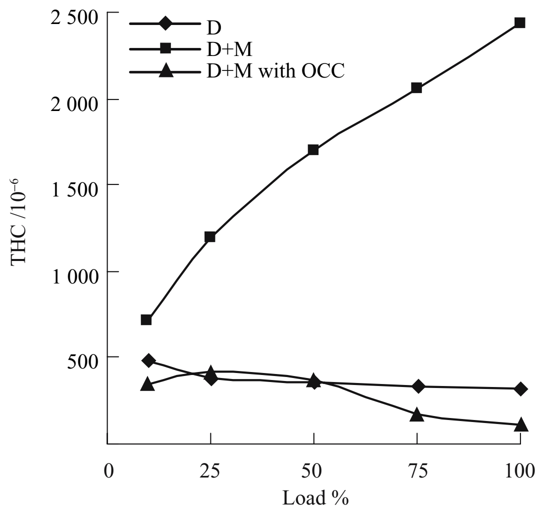

Fig. 6 HC emission at 2 200 r/min

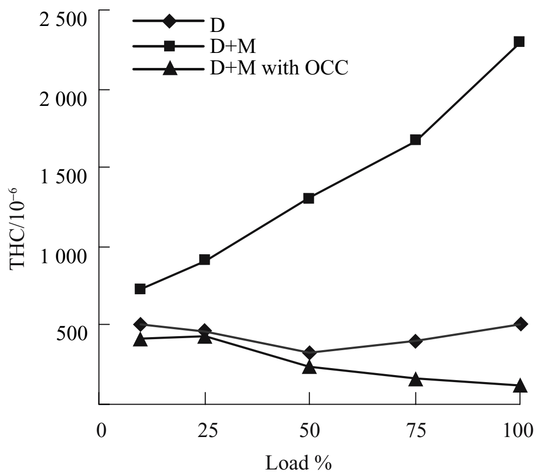

Fig. 7 HC emission at 3 200 r/min

Two reasons account for HC emission without catalyst. The first one is that methanol-air combustible mixture instead of fresh air gets into the cylinder. At scavenging duration, a little combustible mixture is expelled from the outlets valves. The second one is that there are three important approaches of diesel engine to produce HC: the flame quenching near the cylinder surface, narrow crack effect and the lube film adsorb the fuel steam [3]. Methanol reinforces the three effects.

The CO of DMCC model largely comes from the incomplete combustion of methanol. In addition, during methanol combustion, a great deal of CH_3O will be produced, which gives birth to CO shown by the following equation [6]

$$CH_3O + O \rightarrow CO + H_2O + OH \quad (6)$$

With the increase in the load, total excess-air ratio lessens and combustible mixture thickens, which makes the combustion incomplete. Meanwhile, the methanol mixture existing in the clearance of the piston head and the slots of the piston rings flow into the cylinder during the expand stroke, some of which oxidize to CH_3O and turn into CO at last.

Because the gasification latent heat of methanol is great, the intake temperature, combustion temperature and the exhaust temperature are reduced, which affects the oxidation of HC and CO.

3.4 Thirteen-mode test cycle measuring emissions

In order to find out the emission characteristics of DMCC engine, 13-mode test cycle is used to test the exhaust of diesel engine, DMCC engine with and without oxidation catalyst. Table 2 shows the results.

Table 2 Thirteen-mode test cycle emissions

Model	HC/g·kWh^{-1}	CO/g·kWh^{-1}	NO_x/g·kWh^{-1}	PM/g·kWh^{-1}
Diesel	2.06	7.78	13.95	1.00
DMCC without catalyst	8.12	10.67	8.14	2.07
DMCC with catalyst	1.09	2.32	8.6	0.89

It can be seen from Table 2 that there is a great increase in HC, CO and PM emissions at DMCC model compared with that of diesel model. The increase in HC is the largest. On the contrary, there is a 41% of NO_x decrease. At DMCC model with oxidation catalyst, there is a 47% decrease of HC and a 70% decrease of CO, which shows that oxidation catalyst has a great effect on the convention of HC and CO.

The amount of PM at DMCC model without catalyst is twice as much as that of diesel engine. But there is a 57% of PM at DMCC model with catalyst. The reason for this is that PM contains some dissolubility organic substances, which are oxidized by oxidation catalyst. This emphasizes the necessity of oxidation catalyst [7]. Thirteen-model test cycle testing indicates that DMCC with the oxidation catalyst model is a new way to decrease NO_x, HC CO and PM at the same time.

4 Conclusions

1) The DMCC model can decrease NO_x and soot emission of diesel engine at the same time.

2) Oxidation catalyst reduces HC and CO emissions of DMCC engine in large scale, and decreases PM exhaust to certain extent.

3) The DMCC model with oxidation catalyst can decrease NO_x and PM at the same time.

4) Compared with DMCC model without oxidation catalyst, there is a little increase in NO_x emission at DMCC model with oxidation catalyst, but the total amount is still less than that of diesel engine.

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